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**PROJECT FOG DROPS
INVESTIGATION OF WARM FOG PROPERTIES
AND FOG MODIFICATION CONCEPTS**

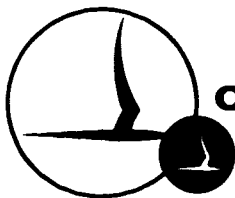
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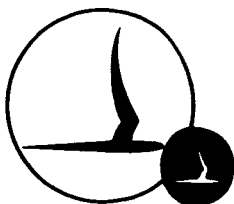
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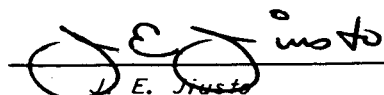
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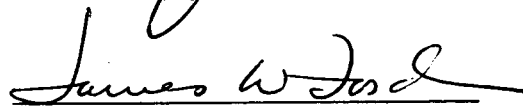

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PROJECT FOG DROPS
QUARTERLY PROGRESS REPORT NO. 1

Period: 1 February 1963 - 1 May 1963

I. INTRODUCTION

Despite improved aircraft landing aids at air terminals, the occurrence of fog continues to hamper flight schedules and transportation. These fogs, for the most part, occur at air temperatures warmer than 0°C , and practical means for their large-scale dispersal are not known. Methods are known for dissipating most supercooled fogs; however, these cold fogs are of secondary importance in this country, being confined to the northern-most latitudes during the winter season.

The need exists for an appraisal of cloud physics mechanisms potentially controllable for warm-fog elimination, and also for a better understanding of the chemical, physical, and electrical properties of natural-fog droplets. Recognizing this need, the National Aeronautics and Space Administration has engaged the Cornell Aeronautical Laboratory, under Contract No. NASr-156, to pursue studies along these lines.

The specific objectives of the first year's research effort are to:

1. Establish physical models of the micro- and macroscopic properties of radiation and advection-type fogs which will define representative values of
 - a. Drop size distribution
 - b. Liquid water content (w)
 - c. Droplet concentration
 - d. Thickness
 - e. Condensation nucleus composition and mass
2. Establish a dynamic model of fog which describes the vertical distribution of temperature, humidity, and liquid water content and, hopefully, the time rate of change of these variables as a function of internal and boundary energy changes.

3. Investigate the molecular characteristics of hydrosols whose droplets are 1 to 100 microns in diameter. Specify, as possible, the normal values of the properties listed below and the manner (and degree) in which these properties might be changed:

- a. Surface tension
- b. Vapor pressure
- c. Droplet surface charge

4. Evaluate the feasibility of fog dispersal concepts associated with three droplet growth mechanisms:

- a. Diffusive growth of droplets with altered surface properties
- b. Coalescence of electrified droplets
- c. Thermal evaporation

5. Perform selected laboratory experiments aimed at

- a. Measurement of the growth rate in a saturated environment of droplets treated with various monolayers.
- b. Measurement of the charge on droplets before and after electrification or treatment with ionic particles.

6. Perform a brief climatological survey of geographic areas (in the U. S.) with a sufficiently high frequency of supercooled fog to warrant an operational seeding program.

This report briefly describes the technical efforts of the first three months of the program and outlines plans for the next quarter. In addition to the individuals whose names appear on the title page, program contributions were made by G. E. McVehil, R. L. Peace, and P. M. Brown.

II. SUMMARY

During the first quarter of the program, the following progress was made:

1. The fog types that affect air terminals in the United States have been identified and grouped into three categories: radiation fog and advection fog, which constitute the so-called air mass fogs, and frontal fog.

2. Based on the above classification and a literature review, physical fog models were devised for radiation fog and advection fog. These models (Table II, Figures 1 and 2) provide quantitative estimates of the micro- and macroscopic structure of fogs necessary in the evaluation of fog modification concepts.

3. A formulation, after Rodhe (1963), was used in two sample cases to define the vertical distribution of fog liquid water as a function of ambient wet-bulb temperature and mixing ratio. The results indicate that this model will be useful in describing the dynamics of fogs caused by the mixing of two air masses with appreciably different temperatures and mixing ratios or fogs with significant radiational cooling at their tops.

4. An analysis was made of the effect of monolayers of fatty acid (e.g. hexadecanol) on fog droplet growth rates on the supposition that such layers might tend to enhance droplet growth, precipitation, and depletion of the fog water. The theoretical analysis indicates that the large decrease in the evaporation (condensation) coefficient of water produced by these layers causes the growth rate of droplets to be greatly retarded. Hence, such monolayers would tend to stabilize fogs rather than to accelerate their decay. A modest gain in droplet growth rate might be realized if monolayer materials can be found that will increase the evaporation coefficient of water. The implications of these monolayers on changes in droplet size distribution and visibility within a fog require further analysis.

5. The well known decrease in evaporation rate of water droplets coated with monolayers in a sub-saturated environment led to a fog control concept worthy of future consideration. Frontal fogs are induced by rain drops falling into dryer air, evaporating, and increasing the dewpoint of the air. If means can be devised for treating these raindrops with monolayers, droplet evaporation might be sufficiently inhibited to prevent fog formation.

6. Laboratory test equipment was partially assembled for checking the droplet monolayer effects, as theorized, and the effect of other materials on droplet behavior. An optical microscope was mounted to enable the observation of droplet growth or evaporation under controlled temperature and saturation conditions.

III. TECHNICAL DISCUSSION

1. Fog Classification

Control of fog can proceed more rationally once a quantitative description of its physical structure is known. During the first quarter, substantial progress was made in categorizing fog types and in establishing a representative physical model of radiation fog and of advection fog.

Fog can form in one of two ways -- by ambient air cooling to its dew-point (air mass fogs) or by the moisture content of the air increasing until saturated conditions are attained (frontal fogs). Mixing of two air parcels is sometimes considered a third way to form fog, although mixing is actually a combination of heat and moisture exchange. There are numerous moisture transport and cooling mechanisms in the free atmosphere by which fog can form, each mechanism being associated with a generic fog type.

The fog classification system employed in our study is based on the classification introduced by Willett (1928) and subsequently modified by Byers (1959). A brief description of the various fog types and the classification system is given in Appendix A. Owing to the limited amount of information on fog structure and to simplify the problem in terms of our project interests, available air mass fog data were lumped into two broad categories -- advection fog and radiation fog. As indicated in Table I, advection fogs, which commonly occur in coastal regions, encompass those fog types in which cooling is caused primarily by the transport of warm air over a cold surface; radiation fogs, which commonly occur inland, comprise those fogs in which radiation constitutes the principal cooling mechanism. More frequently than not, both cooling mechanisms are operative, with one process being dominant.

Table I Fog Classification*

A. <u>Advection (Coastal) Fog</u>	B. <u>Radiation (Inland) Fog</u>
1. land and sea breeze fog	1. ground fog
2. sea fog	2. high inversion fog
3. tropical air (over water) fog	3. advection-radiation fog
	4. upslope fog
	5. tropical air (over land) fog

Air mass fogs, which occur more frequently than frontal fogs, are of major importance on this program. Frontal fogs are associated with active precipitation and an increase in ambient dew point in the vicinity of fronts so that fog control suggests control of associated precipitation; such an ambitious goal would be premature in the light of current cloud modification capability. An alternate, more-realistic concept for controlling frontal fog is offered in the section on "droplet monolayers," III-4.

Ice fogs and "arctic sea smoke" have been deleted from the study since the former occur only at polar latitudes and the latter only over open water.

2. Fog Structure -- Physical Models

A reasonably comprehensive literature survey was conducted in order to construct physical or structural models of radiation and advection fogs as herein defined. Despite the considerable research interest in fog phenomena for some three decades, the amount of consistent data on fog structure is generally too sparse for statistical treatment. The deficiency stems partly from inadequate instrumentation, especially with respect to measurements aloft; partly from the lack of standardization of measured quantities (for example, the "average" size of fog drops may, depending on the investigator, represent the arithmetic or linear mean, volume mean, area mean, median, mode etc); and partly because of the variability in fog characteristics depending on season, locale, and fog type.

* See Appendix A for explanation of fog types. Note that in our classification the coastal fogs initially form over water and subsequently may be transported inland whereas the inland fogs form over a continental area.

While statistically valid measures of pertinent fog parameters are not available, approximately 100 references (of which the most useful are listed in the reference section) enabled the specification of representative fog values. These values, which are presented in Table II, along with Figures 1 and 2. constitute out tentative working models of radiation and advection fogs.

Table II Physical Fog Models

<u>Fog Parameters*</u>	<u>Radiation (inland) fog</u>	<u>Advection (coastal) fog</u>
1. Average Drop Dia.	10 μ	20 μ
2. Typical drop size range	5-35 μ	10-65 μ
3. Liquid water content	110 mg/m ³	170 mg/m ³
4. Droplet concentration	200 cm ⁻³	40 cm ⁻³
5. Vertical depth of fog		
a. typical	100 m	200 m
b. severe	300 m	600 m
6. Horizontal visibility	100 m	300 m
7. Nuclei a. size	0.08-0.8 μ	0.5 μ and greater
b. type	combustion products	chlorides and nitrates

From the standpoint of fog modification, the liquid water content w and its associated vertical distribution is one of the more important characteristics of fog. Figure 1 shows three measured w profiles obtained in (1) an inland fog (Nikandrov 1960), (2) a dense coastal advection-radiation fog (Okita 1962), and (3) a dense sea fog (Hanajima 1945). These three profiles are used (see next page) in tentative assessments of the fog problem. Water profile data are extremely scarce; we hope eventually to provide a general analytic expression for the vertical distribution of fog water, as discussed in Section III-3.

Another important characteristic of fog is its drop size distribution. Based on experimental data from fog and clouds, Best (1951) found that drop size distributions can be represented by the formula

$$I - F = \exp (-x/a)^b \quad (1)$$

*Ground-level values (except item 5).

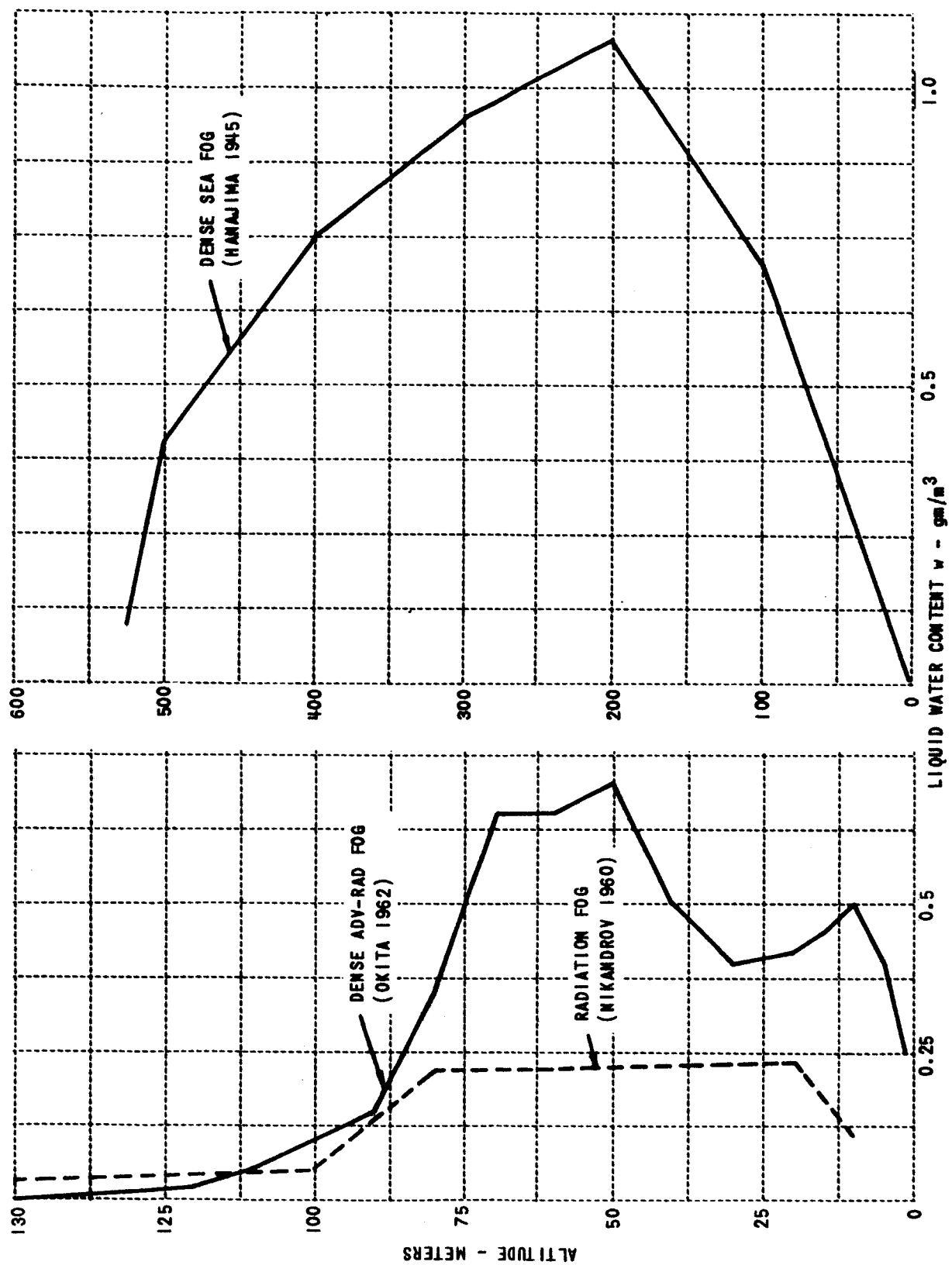


Figure 1 VERTICAL DISTRIBUTION OF LIQUID WATER CONTENT IN FOG

where F is the fraction of liquid water in the air consisting of drops of diameter less than x ; b is approximately 3.3; and a is related to liquid water content w by

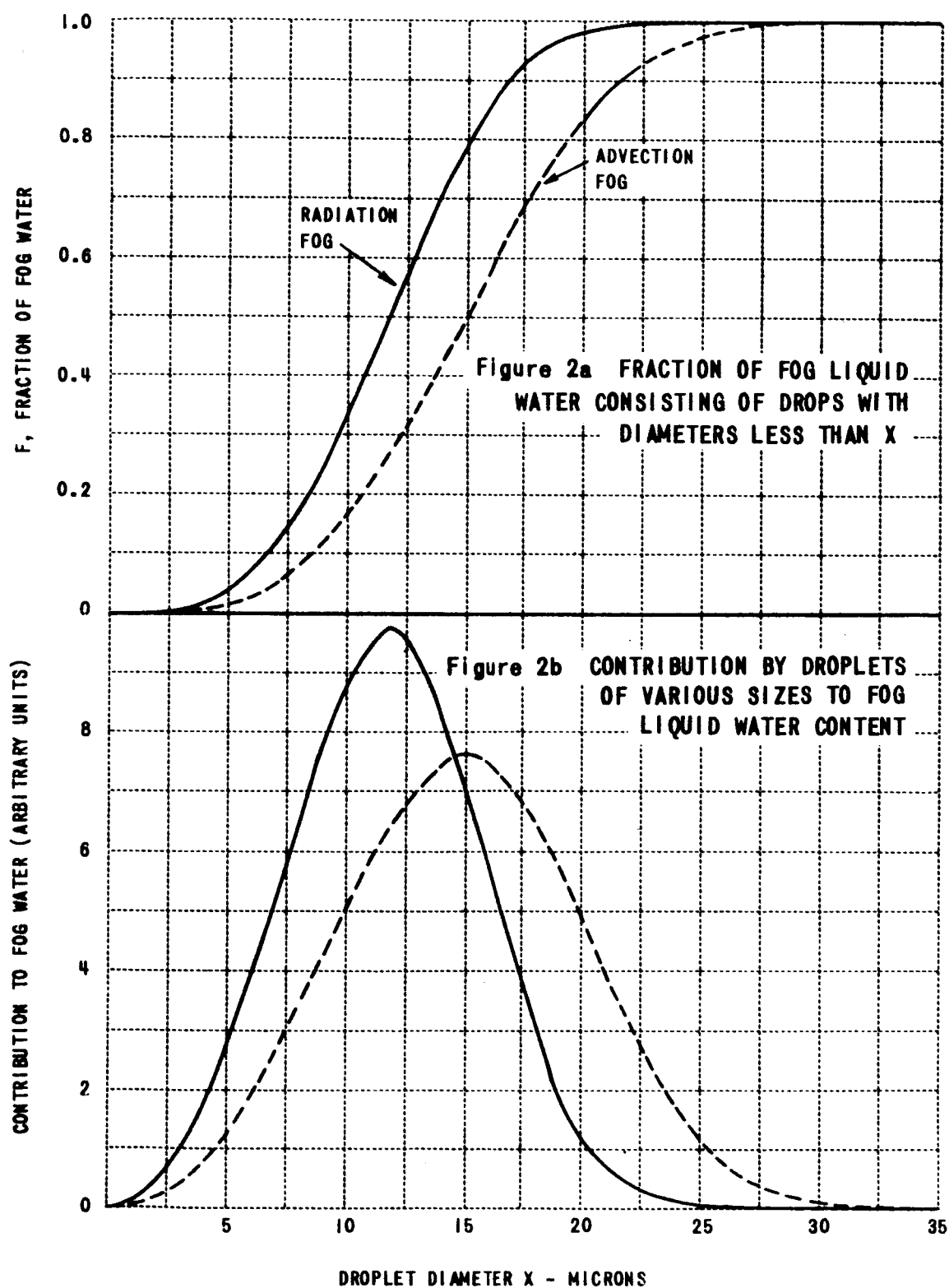
$$w = 1.1 \times 10^{-3} a^{1.79} \quad (2)$$

Values of w were taken from the fog models (Table II) and expressions (1) and (2) tabulated. The results are plotted in Figure 2. These curves show the contributions which the different droplet sizes make to the total liquid water content of the fog. The half widths* of the functions in Fig. 2B extend from 7 to 17 microns for inland fog and from 8.5 - 21 microns for coastal fog. Referring to Figure 2A, it can be seen that each of these droplet-size intervals encompasses approximately 80 per cent of the fog liquid water. The curves suggest that these drop sizes may be of major importance in the development of fog-modification concepts.

One instructive way to assess fog severity and its implications on modification attempts is to evaluate the total amount of condensed water in a vertical column through a given fog. It is convenient to consider a column with a 1-m^2 cross section. For complete fog dissipation, this columnar quantity of water multiplied by the lateral extent of clearing represents the total amount of water that must be either evaporated or precipitated. In practice complete fog dissipation would not be necessary; it would be sufficient merely to improve the visibility within a fog to the point where aircraft landings and take-offs were possible. In this case only a fraction of the total column water need be evaporated or precipitated, or shifted to a different size distribution favoring increased visual range. We will also consider the amount of water in the lowest 100 meters since clearing of fog to this altitude would enable aircraft instrument landings.**

* The width of the line measured between two points at which the function dF is half its peak value.

** ILS (Instrument Landing System) landing limits for jet aircraft involve ceilings and visibilities of 300 feet and 0.75 mile respectively. GCA (Ground-Controlled Approach) minimums are less restrictive than the ILS limits.



Accordingly, we have calculated the total amount of liquid water in a column and the amount of liquid water in the lowest 100 meters for the three fogs indicated in Figure 1. The results are tabulated in Table III.

Table III Fog Water Content

	<u>Inland Fog (Radiation)</u>	<u>Coastal Fog (Adv-Rad)</u>	<u>Coastal Fog (Sea Fog)</u>
1. Depth of fog	150 m	130 m	550 m
2. Total liquid water in 1-m ² column	20.8 g	46.2 g	390 g
3. Total liquid water below 100 meters in 1-m ² column	19.4 g	45 g	35 g
4. Total liquid water in arbitrary runway "zone" (100 m high, 50 m wide, 2000 m long)	1940 kg	4500 kg	3500 kg

These fog water values help us not only to grasp the scope of the problem but also to calculate energy requirements for suggested modification concepts. One revealing feature of the table is that the total water in the lowest 100 m of these markedly different fogs varied by only a factor of two -- this despite the fact that the extremely dense sea fog contained about 19 times as much total condensed water as the typical inland fog. This feature of fogs, if representative, could be an encouraging factor in fog modification.

3. Dynamic Fog Model

We are formulating fog models in order to specify the vertical distributions of temperature, water vapor, and liquid water, in different types of fog. Such models, if obtainable, will first of all extend our limited knowledge of these basic fog properties. Secondly, information derived from these models will permit us to study the role of different physical mechanisms which contribute to fog formation. This information will be useful in assessing the potential of suggested fog modification techniques.

Three mechanisms have been suggested and frequently called upon in the past to explain radiation and advection fogs: 1) direct radiational cooling of the air and already existing fog, 2) cooling of the earth's surface, leading to transport of heat from the air to the ground, and 3) mixing of moist air masses with different initial temperatures. Over the years there have been numerous attempts to assess the relative importance of these three factors in the production of different types of fog. Most investigators have sought to demonstrate the predominance of one factor. For example, Emmons and Montgomery (1947) showed, with certain assumptions, that it was not possible to produce supersaturation by cooling an air mass from below. They therefore concluded, as have others, that fog was usually the result of radiational cooling of the air. Taylor (1917) also decided that turbulent transfer of heat to a cold surface would not cause fog, but he explained observed advection fogs on the basis of mixing of warm and cold masses of moist air. Lyons et al. (1962) state that this mixing effect is so small as to be negligible and, therefore, that radiational cooling is the most important cause of fog. The apparent differences of opinion stem partly from the fact that, different types of fogs were involved.

In a recent paper, Rodhe (1962) comprehensively reviewed the subject of fog formation and suggested that two or more factors are usually important in any natural fog. Rodhe's conclusions point up the importance of the mixing process, but he also shows how radiational effects contribute. Like previous authors, Rodhe minimizes the importance of direct cooling of the air by molecular and eddy heat conduction, but his mathematical formulation makes it possible to retain this effect if it does contribute. Therefore, we have used his analysis as a starting point in our formulation of a dynamic fog model.

The vertical eddy flux of total heat H in the boundary layer will be

$$H = -\rho \left[C_p + T' \frac{d}{dT'} \left(\frac{Lv'}{T'} \right) \right] K_H \frac{\partial T'}{\partial z} \quad (3)$$

and similarly, the vertical eddy flux of total water content E is

$$E = -\rho K_E \frac{\partial r}{\partial Z} \quad (4)$$

In the equations, ρ is the density of the air, Z is the vertical coordinate, L is the heat of vaporization, K_H and K_E are the eddy exchange coefficients for heat and water, respectively, T' is wet-bulb temperature, the term in brackets in (3) is the specific heat of moist air, and r is the total water mixing ratio equal to the sum of the saturation mixing ratio v' and the liquid water w .

The vertical flux of water may be rewritten

$$E = -\rho K_E \frac{\partial r}{\partial T'} \frac{\partial T'}{\partial Z} \quad (5)$$

where we consider the total differentials dr and dT' to be evaluated over vertical differences only; i.e. $dr = (\partial r / \partial Z) dZ$ and $dT' = (\partial T' / \partial Z) dZ$. Now, eliminating $\partial T' / \partial Z$ between equations (3) and (5), we obtain a differential relation between water content and wet-bulb temperature:

$$\frac{dr}{dT'} = \frac{E}{H} \frac{K_H}{K_E} \left[c_p + T' \frac{d}{dT'} \left(\frac{L v'}{T'} \right) \right] \quad (6)$$

Equation (6) is given by Rodhe except that he assumes $K_H = K_E$. We retain the ratio K_H/K_E simply as a reminder that theoretically the effect of different exchange coefficients can be taken into account.

The application of this fundamental result, equation (6), can be demonstrated with reference to a T', r diagram, similar to the temperature, vapor pressure diagram used by Taylor (1917) in his classic description of fog formation. In Figure 3, the curved solid line represents the relation between wet-bulb temperature (= dry bulb temperature at saturation) and saturation mixing ratio at a pressure of 1000 mb. The dashed line is one possible integral of equation (6), with E/H and K_H/K_E constant. Where the dashed curves lies to the left of the solid curve, the state is one of supersaturation, and fog would exist. The amount of liquid water at any temperature is given by $r - v'$; i.e. the distance between the saturation curve and the actual curve. The dashed line shown in the example might result from an advection fog situation. If air at some upper level, Point B, is at a wet-bulb temperature of 11°C and relative humidity of 93%, and the corresponding

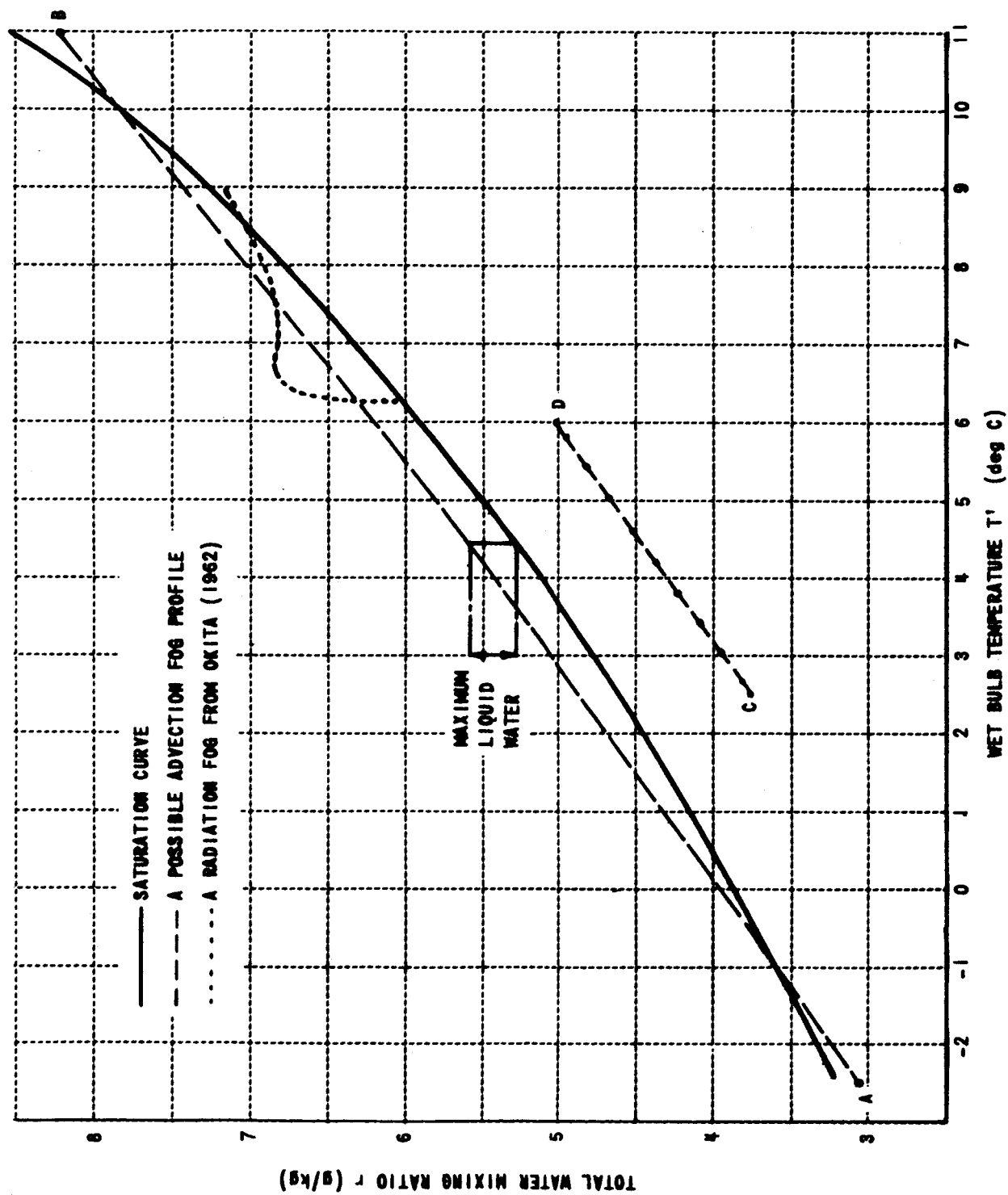


Figure 3 PHASE DIAGRAM OF FOG FORMATION

surface conditions are -2.5°C and 91 percent, supersaturation will exist at the intermediate levels indicated. The figure shows that liquid water contents of up to 0.3 g m^{-3} could be realized in the fog. For two air masses represented by points C. and D, it is evident that mixing could not produce supersaturation or fog.

Two conclusions follow directly from the discussion thus far. First, in the simple case where the ratios E/H and K_H/K_E are constant (for these conditions the temperature and total water profiles are similar), fog can be formed in the surface boundary layer if the air is near saturation in the higher levels. Though moisture is withdrawn from the air by vertical eddy diffusion, supersaturation can occur at intermediate levels. Secondly, substantial temperature differences between air parcels are needed to give appreciable liquid water. Thus, the pure mixing mechanism may be adequate to explain advection fogs where the air mass is considerably warmer than the underlying surface, but the effect does not seem large enough to explain many observed fogs where vertical temperature gradients through the fog are weak.

To obtain higher liquid water content with small temperature differences, we must consider cases for which E/H is not constant with height. The most important effect which would lead to variation of E/H is radiational cooling of the air and fog. If one part of the boundary layer is losing energy by radiation, turbulent heat transport acts to balance the losses; thus H will vary in the vertical. There is no reason to expect E to change with height in this situation and as a result, E/H is no longer constant and the T', r curve may have an entirely different shape from that for constant E/H .

The previously mentioned advection-radiation fog documented by Okita (Section III-2) enabled a curve of T' vs r to be plotted (dotted line in Figure 3). A crude calculation of the radiation required to produce such a curve has been made and our results indicate that radiational cooling of the fog top was essential in the growth and maintenance of the fog.

The two examples presented here have shown how Rodhe's formulation leads to a description of the water content of fog. In the first example, mixing alone was used to explain the formation of a fog. In the second case, mixing had to be combined with the effects of radiational cooling to yield a representative distribution of water content in an observed fog.

The foregoing ideas provide a basis of understanding of fog formation and properties. To complete the development and arrive at functional models of different fog types, the following work will be carried out. Observations of temperature and, in the few cases available, water content, will be analyzed to determine the basic features of typical fogs. This will permit the estimation of parameters involved in Equation 6. In addition to fog data reported in the literature, we will make use of local Weather Bureau data obtained during the occurrence of Buffalo fogs. Recently two such sets of data were obtained for an advection fog and a frontal fog. The observations will be supplemented by the theory of turbulent transport and radiative exchange. The results will then be utilized to construct models of fog corresponding to pure advection fogs, advection fogs modified by radiational cooling, and fogs arising purely from nocturnal cooling of the air and ground. Since many fogs, particularly the more-or-less pure radiation fogs, are not steady-state phenomena, it may prove necessary to model such fogs in several stages of development.

4. Alteration of Droplet Surface Properties

Over much of its life cycle, fog represents a system in equilibrium i. e. water droplets in equilibrium with vapor molecules. Under consideration in this program are droplet properties, both electrical and thermodynamic in nature, which, when altered, might bring about a condition that will upset this equilibrium. The droplet properties under consideration are temperature, vapor pressure, evaporation (or condensation) coefficient, * rates of condensation and evaporation, charge of the droplets, and surface tension.

*The evaporation (or condensation) coefficient of a liquid is by definition the ratio of the observed rate of evaporation under given conditions to the "expected" rate based on the existing saturation vapor pressure.

These are not to be thought of as independent properties since a change in one may directly or indirectly alter the other properties.

We are currently assessing the effect of insoluble monomolecular films (such as the fatty acids hexadecanol and octodecanol) on the physical properties of water droplets. Numerous investigators, notably Bradley (1955), have studied the rate of evaporation of bulk water and droplets treated with various monolayers. The results are in general agreement: in a sub-saturated environment, the evaporation rate of bulk water and, to a greater extent, small droplets will be greatly retarded. For example, Eisner et al. (1958) measured the lifetime of 10μ diameter droplets at 20°C and 80 percent relative humidity to be 0.64 second for pure water and 656 seconds for water treated with a monolayer of cetyl-stearyl alcohol. The evaporation reduction is accompanied by a marked decrease in the evaporation coefficient (0.04 to approximately 10^{-5} - 10^{-6}), a four-fold decrease in surface tension, and an alteration in electrical properties of the droplet surface.

As stated in Section III-1, frontal fogs are caused by precipitation falling into a colder air mass, whereupon partial evaporation of the rain drops increases the ambient dewpoint until fog is formed. Clearly then, "stabilization" of the rain drops with monolayers would retard evaporation and conceivably inhibit fog formation. The sizeable task of effectively treating the rain drops or perhaps the cloud prior to precipitating is as yet an undetermined factor.

We have considered the possibility of treating fog droplets with monolayers to increase their growth rate in a slightly super-saturated environment. Our analysis indicates that, at least for the insoluble monolayers currently in use, the hope for an increase in droplet growth rate can be dispelled. In fact the growth rate of treated droplets in a super-saturated environment is expected to be greatly retarded just as the evaporation rate is decreased in a subsaturated environment. (There are other areas of weather control where this effect may be of use.) The following discussion will illustrate the principles involved.

Eisner, Quince, and Slack (1960) have shown, using an equation based on one derived by Fuchs (1959), that droplet evaporation can be expressed by

$$\frac{dm}{dt} = \frac{4 \pi MD}{RT} (f P_T - P_\theta) \frac{a}{1 + D/a \gamma \alpha} \quad (7)$$

where

$\frac{dm}{dt}$	is the rate of evaporation or growth (g/sec) of a droplet of radius a
M	the molecular weight of the liquid
D	the diffusion coefficient for the vapor into the air
f	the relative humidity expressed as a fraction
P_T	the vapor pressure of the liquid at the ambient absolute temperature T
P_θ	the vapor pressure of the liquid at the droplet temperature
R	the universal gas constant
γ	molecular mobility equal to $(R^T/2\pi M)$
α	the coefficient of evaporation (or condensation)

In the case of a super-saturated environment, the relative humidity fraction f is slightly greater than 1. For droplet growth to be maintained, fP_T must be greater than P_θ . For a drop growing by diffusion, the released latent heat of condensation causes the drop temperature θ to exceed ambient temperature T ; hence we have $P_\theta > P_T$. Thus, it is evident that heating of a water drop during diffusional growth reduces the vapor pressure difference between drop and environment and slows the growth rate.

To observe the effect of a monolayer on droplet temperature, consider the expression of Johnson (1950):

$$\theta = T + \frac{LMD}{KRT} \cdot \frac{(fP_T - P_\theta)}{(1 + D/a \gamma \alpha)} \quad (8)$$

The evaporation coefficient α for water is approximately 0.04; with a fatty acid monolayer, α is reduced to 10^{-5} to 10^{-6} . By the insertion of representative (model) fog values for the other quantities in (8), it can be shown that the monolayer causes $\theta \approx T$. The vapor pressure differential ($fP_T - P_\theta$) is thereby maximized, suggesting an increased droplet growth (approximately twofold for our typical fog conditions) from this term alone.

However, returning to Equation (7), converting droplet mass m to diameter a , and integrating we obtain

$$t = \frac{RT\rho}{8MD(fP_T - P_\theta)} \left[\frac{a^2 - a_0^2}{2} + \frac{D(a - a_0)}{\gamma\alpha} \right] \quad (9)$$

which represents the time required for a drop of diameter a_0 to grow to size a . The monolayer affects the quantity ($fP_T - P_\theta$) favorably as indicated above, but the second term in brackets $D(a - a_0)/\gamma\alpha$ is increased by approximately a factor of 10^4 . Thus theory predicts that the growth rate of a droplet coated with a fatty acid monolayer will be greatly retarded. We are not presently aware of monolayers that would cause α to increase.

4. Laboratory Experimentation

We are currently preparing a test chamber that will allow us to study the behavior of droplets suspended from fibers of low thermal conductivity. An optical microscope has been mounted to enable observation of droplet growth or evaporation when the droplets are subjected to various physical-chemical changes (monolayers, ionic fluids, etc.). The temperature, humidity, and saturation ratio of the test chamber will be controllable over ranges representative of warm fog conditions.

The first brief experiments contemplated involve verification of the monolayer effects as theorized in the preceding section.

IV. FUTURE PLANS

Plans for the next reporting period include the following efforts:

1. Extend the dynamic fog model work in order to provide representative vertical profiles of liquid water content under a variety of atmospheric conditions.
2. Complete the droplet test chamber and measure droplet growth as influenced by various monolayers.
3. Commence the study of fog droplet coalescence and feasible methods of enhancing this process.

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3. Advection-Radiation Fog: this fog is caused by nighttime radiational cooling of air that has moved inland from the sea during the day. (Great Lakes during fall, California Coast.)

4. Upslope Fog: involves cooling of air to its dewpoint by adiabatic expansion as the air moves to higher elevations. This fog can be maintained in relatively high winds. Usually nocturnal, radiational cooling is also needed to cool the air to its dewpoint. (Great Plains.)

B. FRONTAL FOGS

1. Prefrontal (warm front): rain falling into stable cooler air evaporates and raises the dewpoint of the air to the condensation point. A low-level continental-polar air mass is most favorable for its occurrence as is the presence of a nearby secondary low which produces a weak pressure gradient and light winds. (Mid- and North-Atlantic coast states in winter; Appalachian valleys.)

2. Post-frontal (cold front): very little difference from B-1 except that the associated precipitation band is much more restricted in area. The air in both cases must be stable or cumuliiform clouds will form. (Midwestern U. S. during polar air mass outbreaks.)

3. Front-passage fog: a short-lived fog that can form in a variety of ways (mixing of two moist air masses of different temperatures, sudden cooling of air over moist ground, etc.) with the passage of a frontal zone.

C. ICE FOG

Fog caused principally by man-made sources of moisture (combustion) at temperatures colder than about -30°C . (Polar regions.)

APPENDIX A

Fog Types and Classification - After Willet (1928) and Byers (1959) (Examples of Regions of Occurrence in Parentheses)

A. AIR MASS FOGS

1. Advection

a. Land- and sea-breeze fog: warm, moist, land air in passing over cold water is cooled to the dewpoint. The fog is transported over land by afternoon sea breezes. (Summer phenomenon along New England coast.)

b. Sea Fog: like a. except that it arises from the cooling of sea air over a cold ocean current or cold coastal current. (Outer California coast in summer.)

c. Tropical-air Fog: caused by gradual cooling of tropical air as it moves poleward over the ocean or over land. (Most common open-sea fog type; causes widespread fog in the south-eastern U. S. and east coast of the U. S.)

d. Steam Fog: advection fog caused by the passage of cold air over warmer water. This fog, which is strictly an over-water phenomena, is called "arctic sea smoke" in polar latitudes.

2. Radiation: nearly all fogs over land are wholly or partially due to radiational cooling of lower-level moist air.

a. Ground Fog: simplest type involving light winds, clear skies, and a surface temperature inversion. Its duration is confined to a single night. (Appalachian valleys)

b. High Inversion Fog: a winter time, land phenomenon resulting from more than a single night of cooling. The inversion extends through a deeper layer 100 to 600 m above ground often with a lower isothermal layer. (Low valleys of the far west in Winter.)